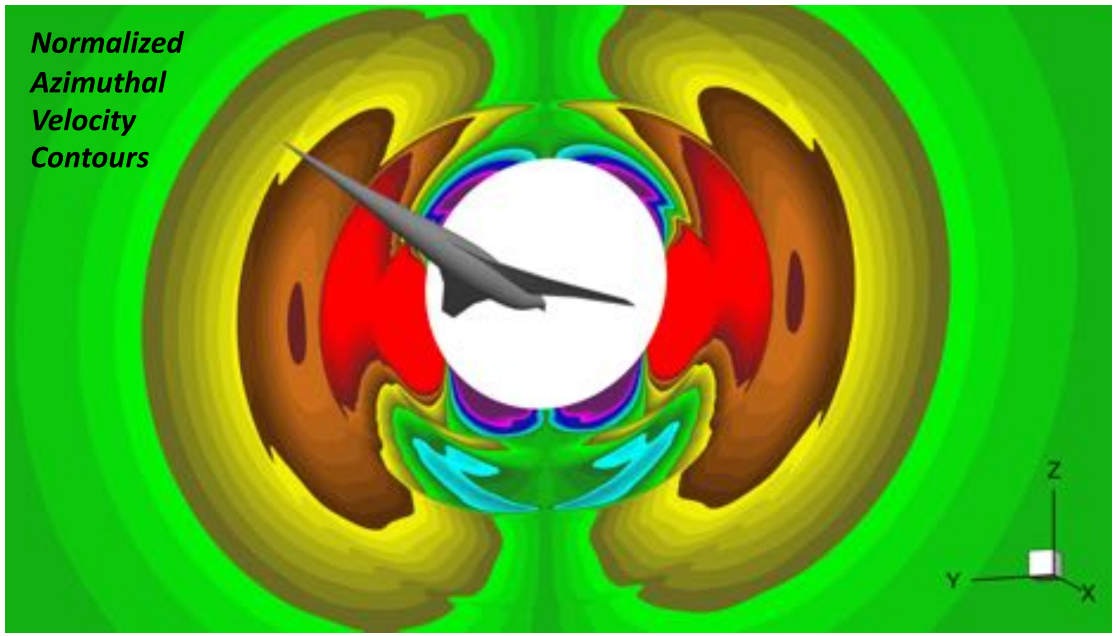
Efficient Near-Field to Mid-Field Sonic Boom Propagation using a High-Order Space Marching Method*



*funded by the NASA's ARMD Commercial Supersonic Technologies (CST) project

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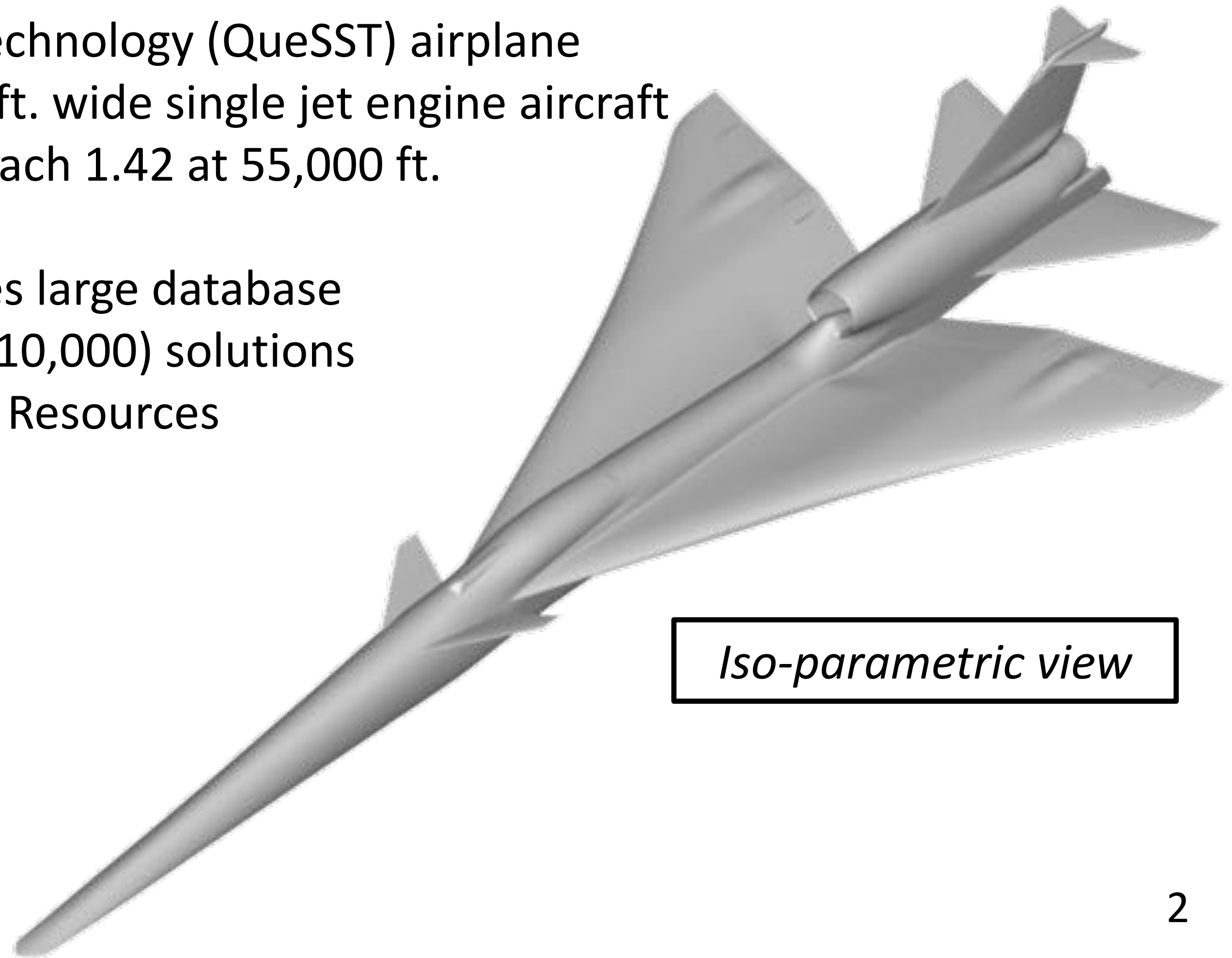
Introduction

NASA's Low-Boom Flight Demonstration (LBFD) project

- Primary goal is to demonstrate feasibility of supersonic over-land flight at reduced loudness levels

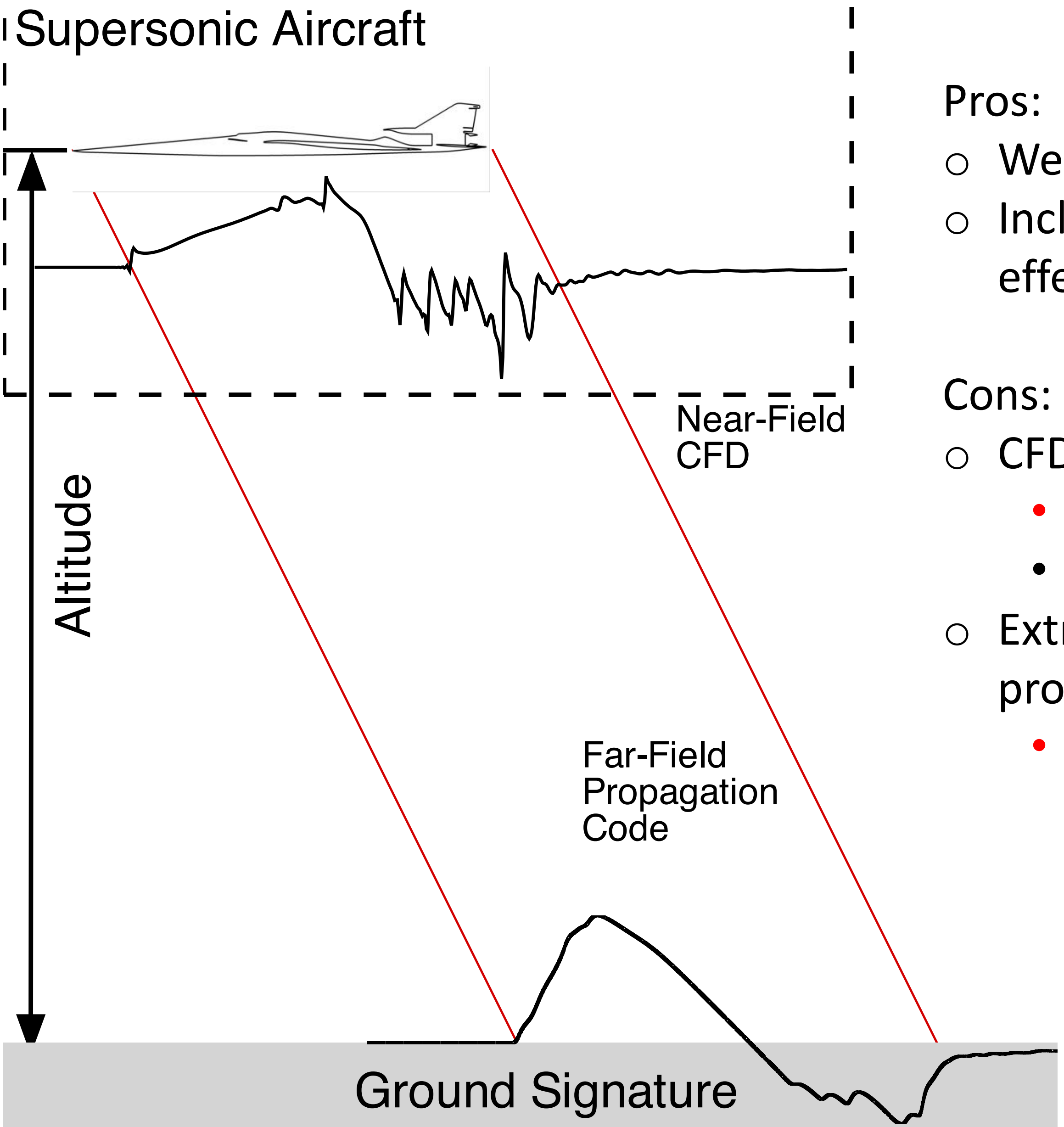
- X-59 Quiet Supersonic Technology (QueSST) airplane
  - 94 ft. long and 29.5 ft. wide single jet engine aircraft
  - Designed to fly at Mach 1.42 at 55,000 ft.

- Mission planning requires large database consisting of *O*(1000)-*O*(10,000) solutions
  - High Computational Resources
  - Must be automated
  - Must be accurate



Iso-parametric view

2-Step Ground Level Noise Prediction



Pros:

- Well established procedure
- Includes important atmospheric effects

Cons:

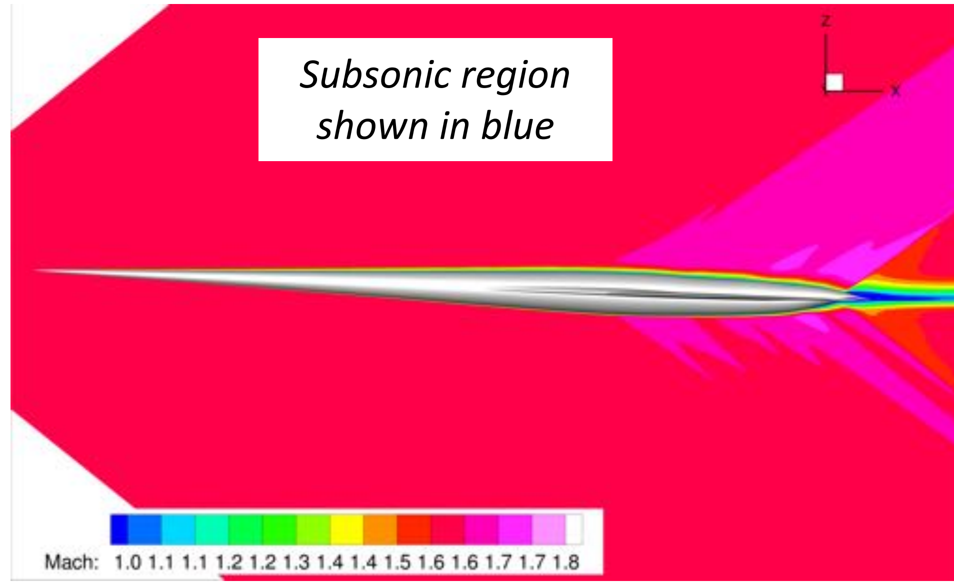
- CFD domain is relatively large
  - High Computational Cost
  - Accuracy (2nd order)
- Extraction radius for far-field propagation relatively small
  - Ignores azimuthal effects

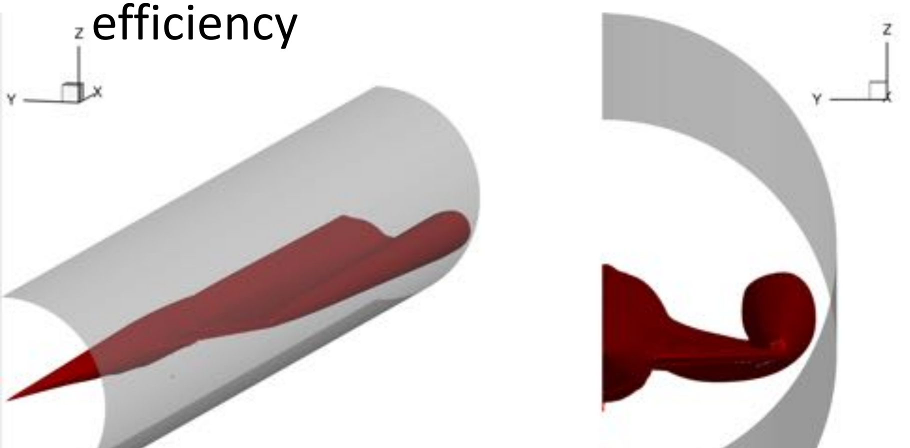
Special Features of Supersonic Flow

- All information travels in a common “time-like” direction along characteristic surfaces

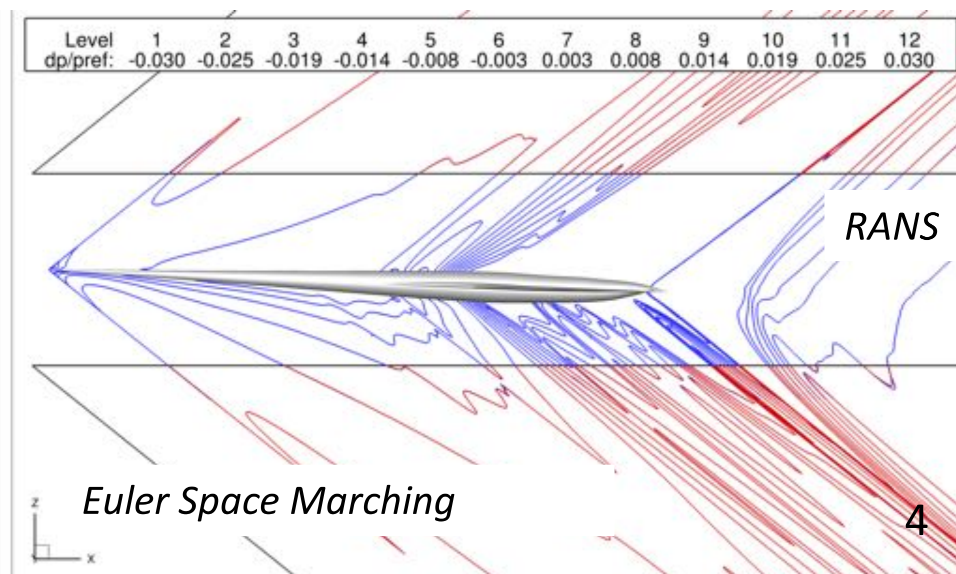
- Viscous effects are only important near the walls of the aircraft

- Space marching is a special discretization/solution strategy which uses these features for computational efficiency

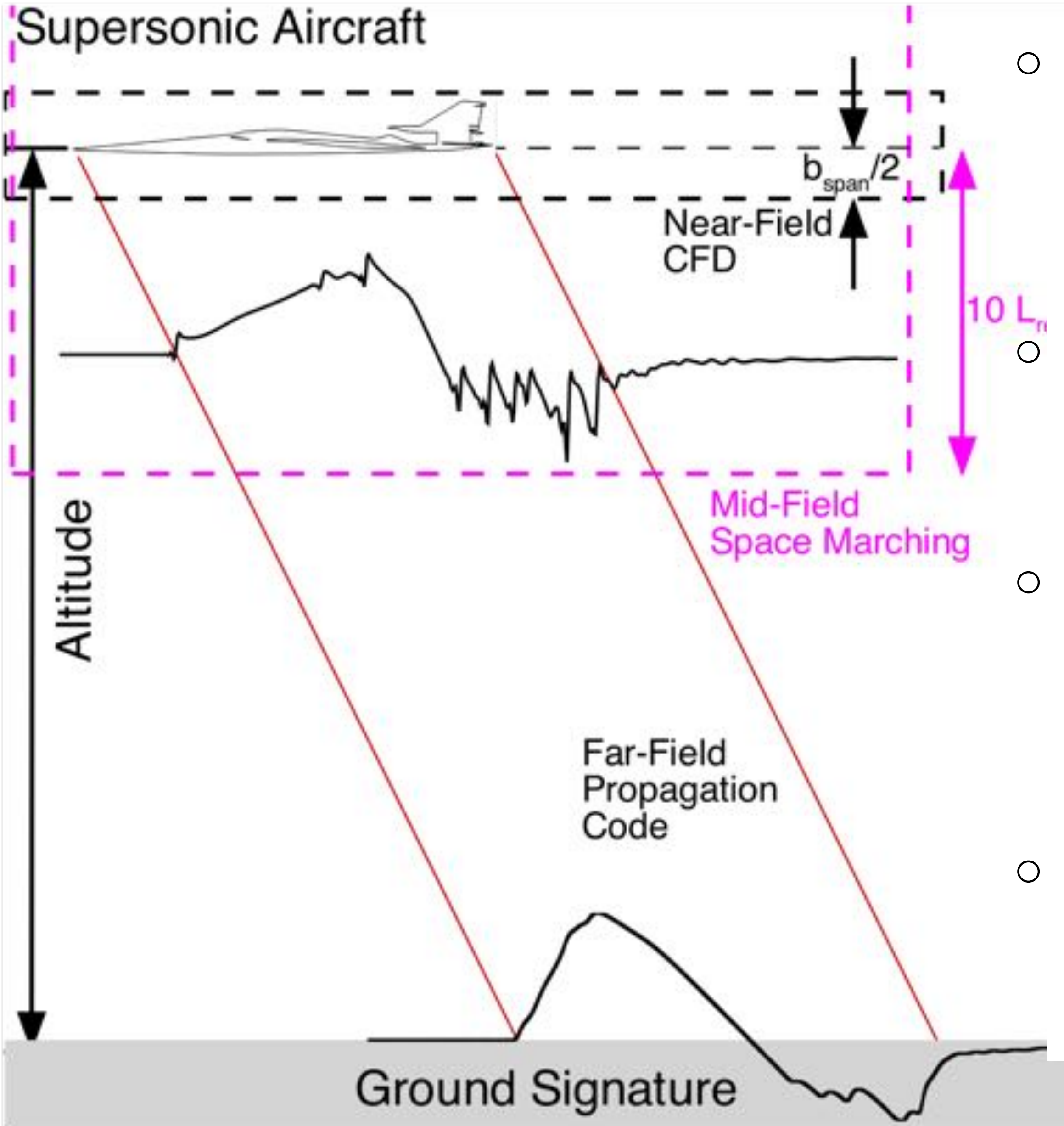




Isocontour of turbulent eddy viscosity ratio (μ_T/μ_∞ = 10)

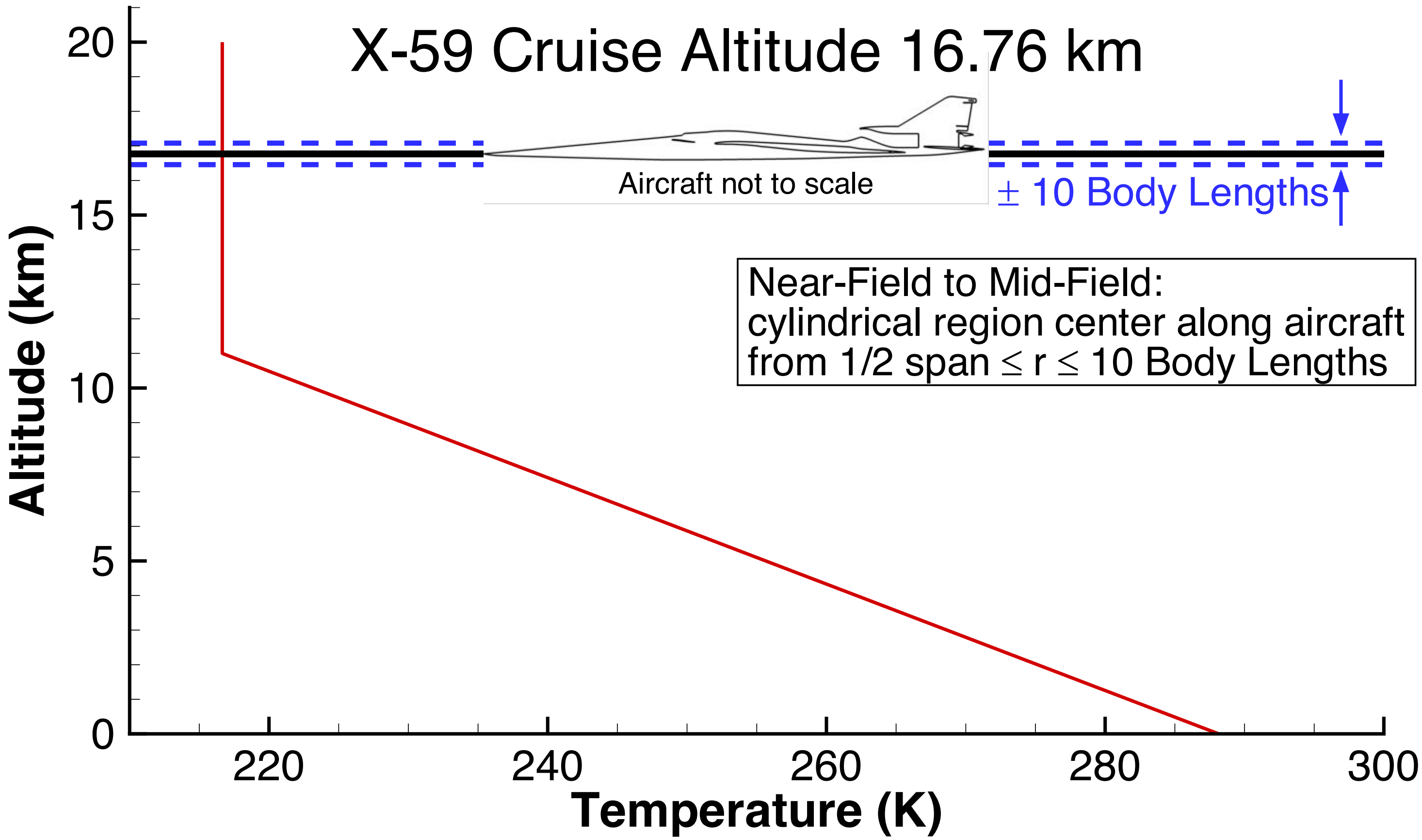


3-Step Ground Level Noise Prediction



- Pros:
  - Reduced CFD domain
  - Space marching procedure:
    - Automated grid generation
    - Runs on workstation in minutes
    - Includes all relevant azimuthal effects
    - Changes from 3D steady into 2D "unsteady-like"
  - More than 50% reduction in total time
  - Same level of accuracy for ground level noise
- Cons:
  - Introduces additional step in process

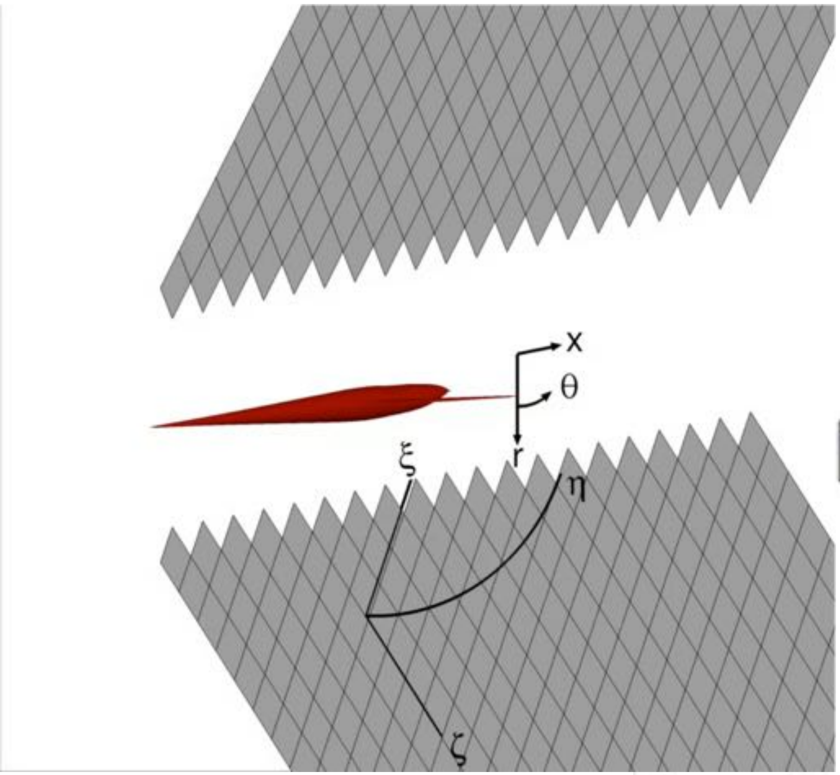
Definition of Near-Field to Mid-Field

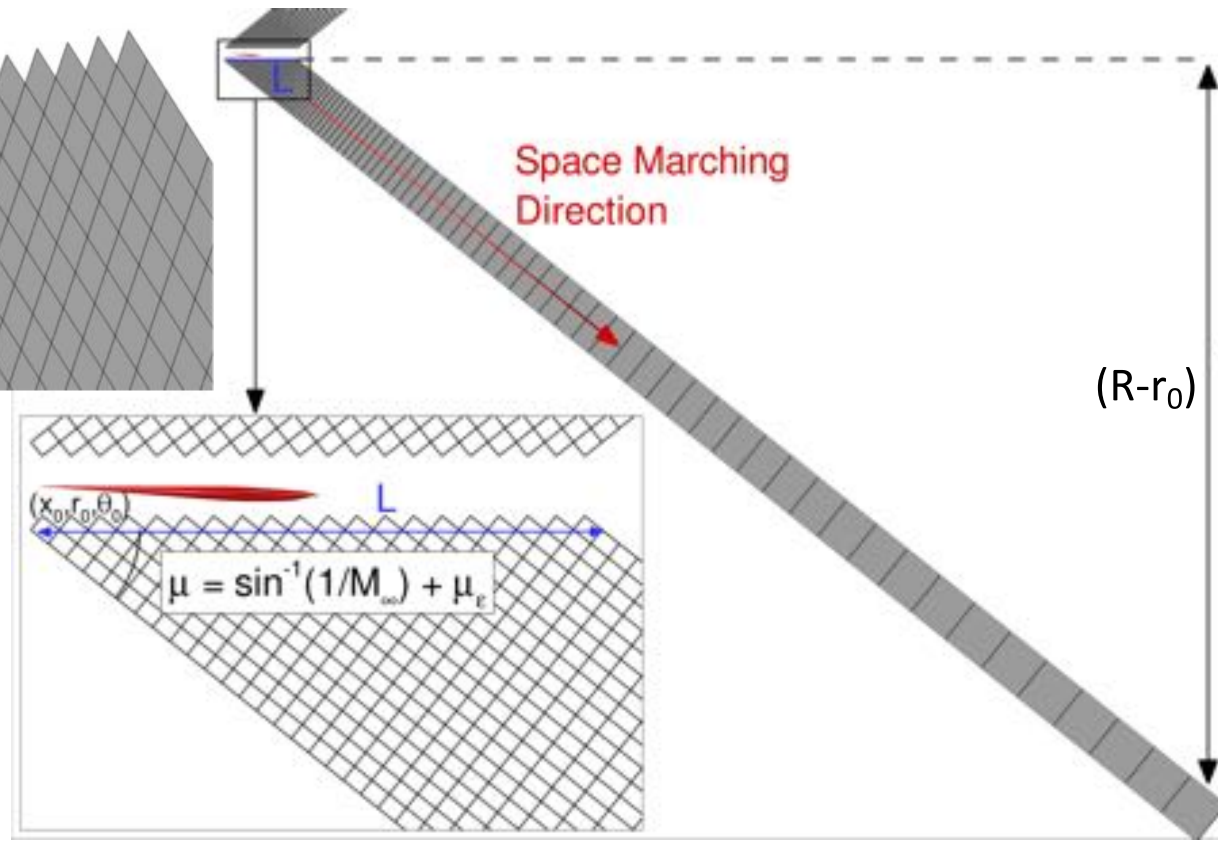


- Plot of altitude versus ICAO standard atmospheric temperature
- No variation in temperature within 10+ body lengths of the aircraft
- Atmospheric effects are neglected in the current approach
  - examples: wind variation, molecular relaxation, and humidity

Mach-cone Aligned Space Marching Grid

- Mach-cone aligned to reduce effect of artificial dissipation
- Small perturbation in alignment to reduce chance of numerical flux crossing sonic line
- Orthogonal to preserve supersonic Mach number in space marching direction

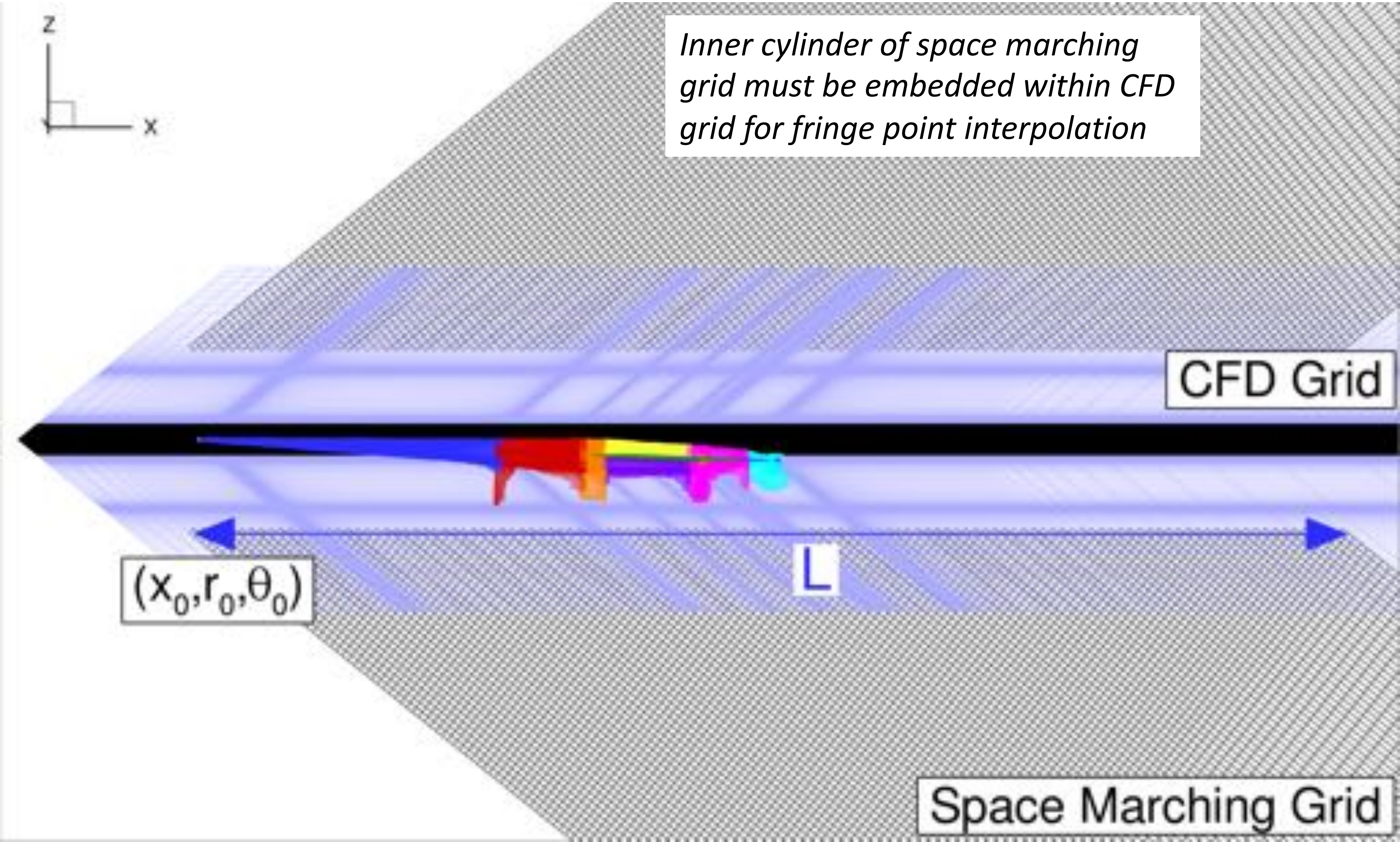




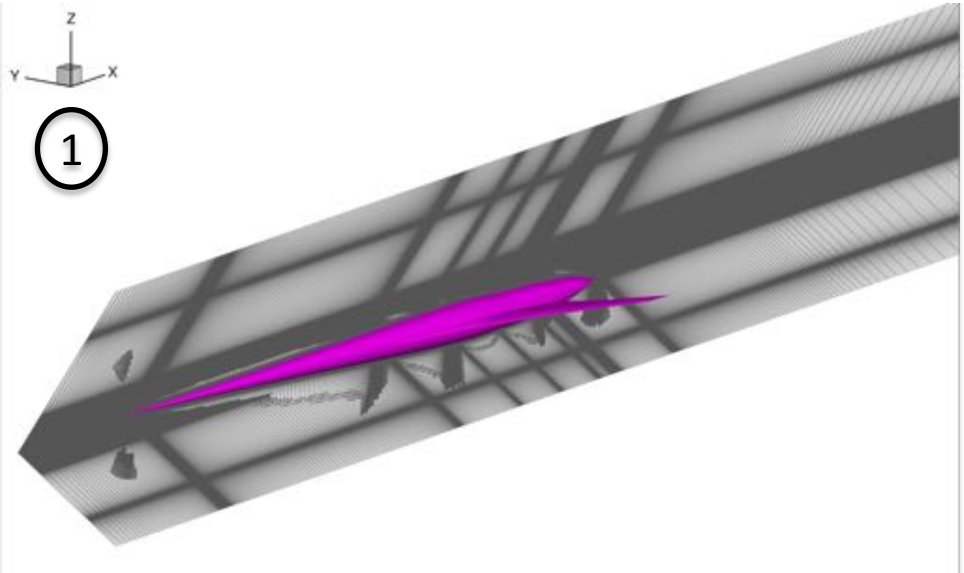
- Standalone grid generation code with limited input parameters
- Generates $O(10)$-$O(100)$ million grid point grids in seconds on a workstation

Mach-cone Aligned Space Marching Grid

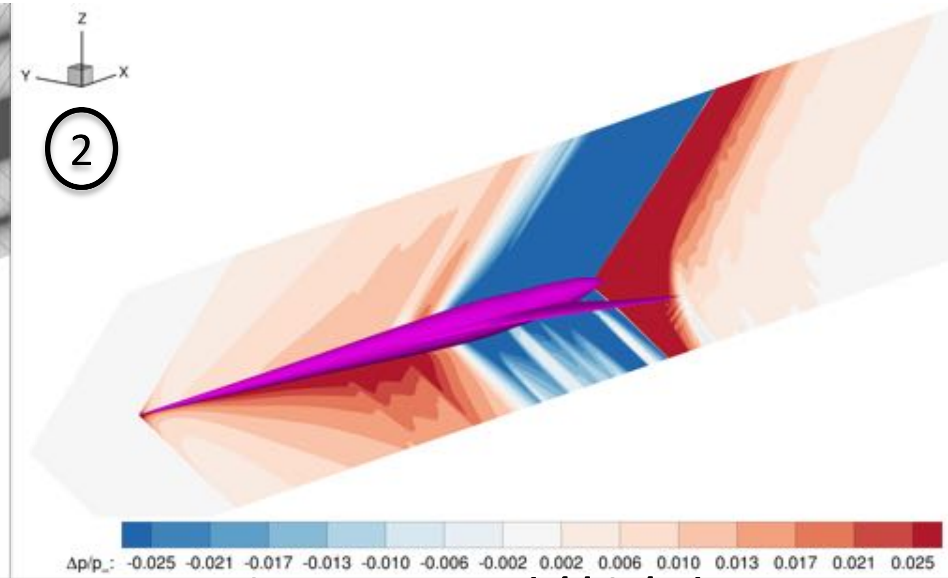
Symmetry plane view of space marching grid and CFD grid



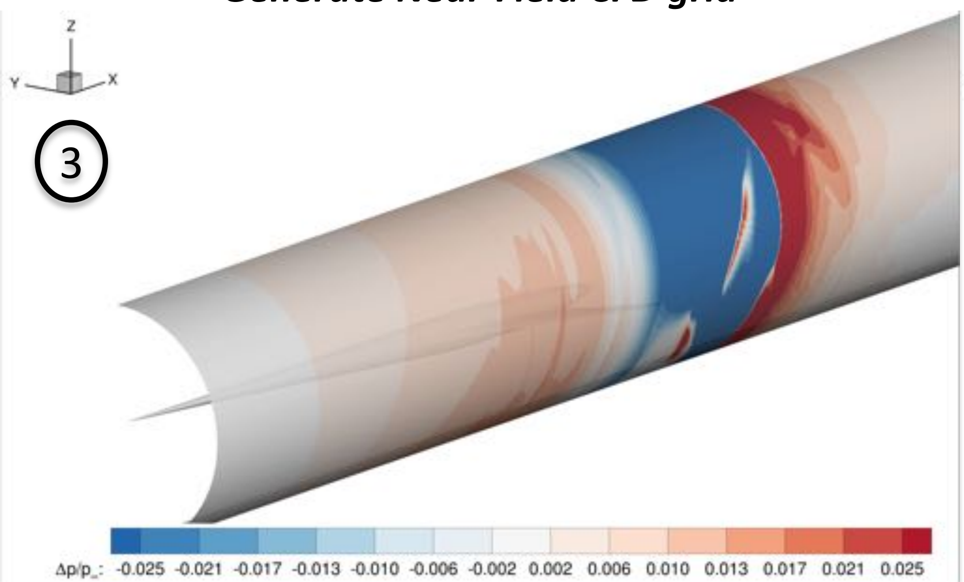
Near-Field to Mid-Field Procedure



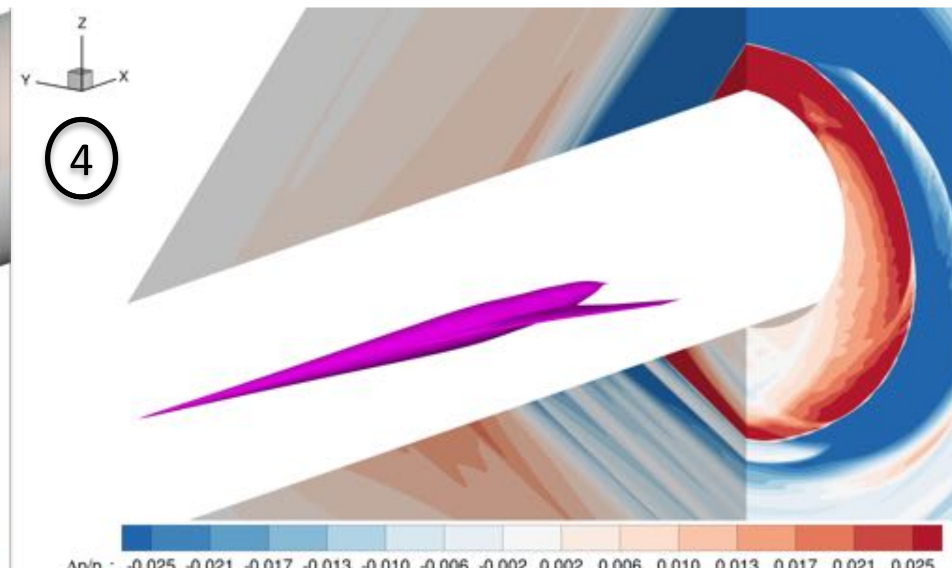
Generate Near-Field CFD grid



Compute Near-Field Solution



Interpolate Fringe Points



Space March through Mid-Field

Numerical Discretization (Space Marching Propagation)

- Governing equations are the steady-state 3D Euler equations transformed to a general curvilinear coordinate system in strong conservation law form

- Second-order BDF2 is used in the space marching direction

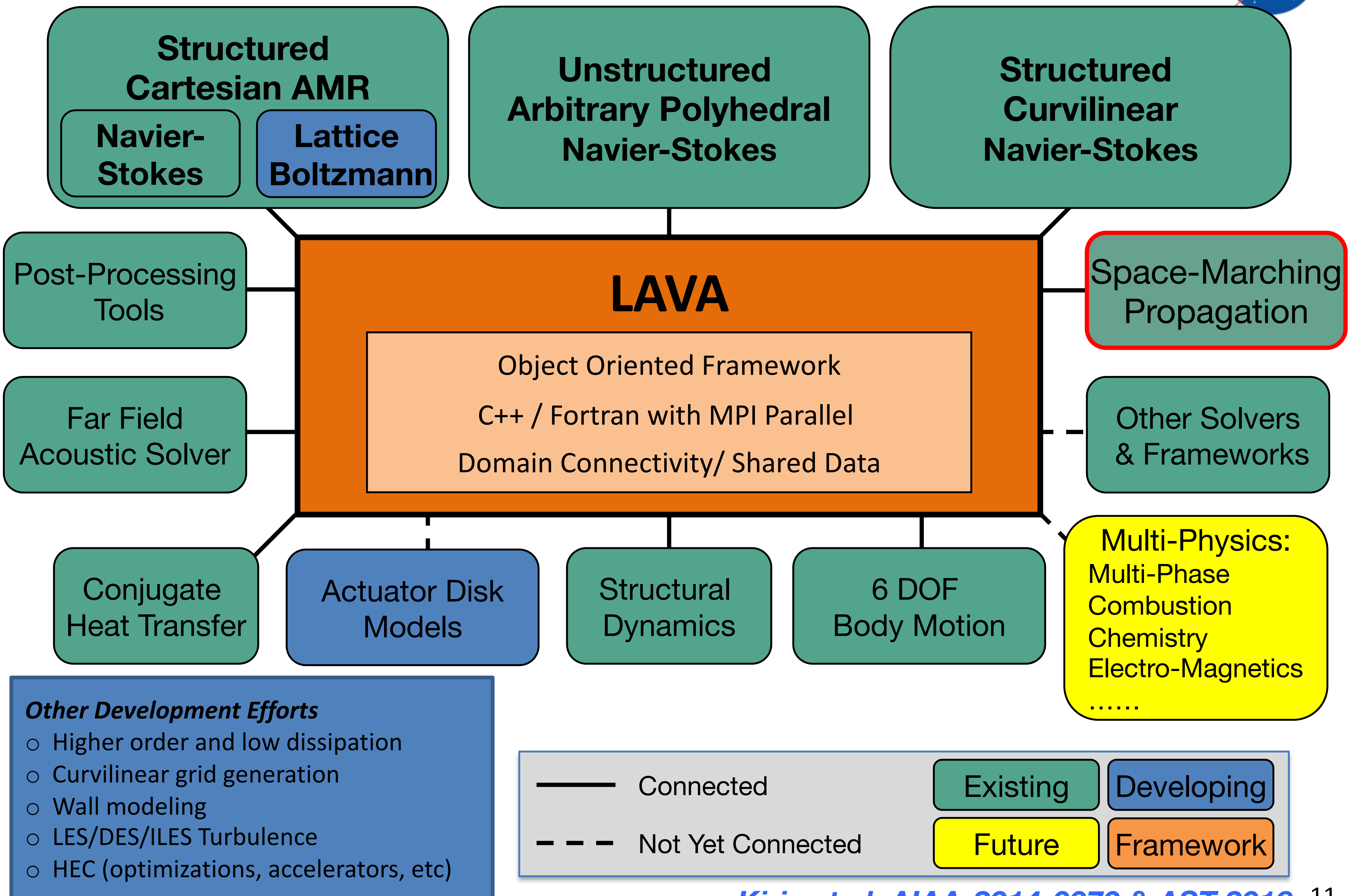
- High-order Hybrid Weighted Compact Nonlinear Scheme (HWCNS) is used in the other two coordinate directions
  - Interface (half-point) fluxes are evaluated with modified Roe
  - Left/Right interface states use 3^{rd} or 5^{th} order WENO interpolation
  - 4^{th} order centered finite difference using a combination of fluxes at the grid points and the half-points

- Identical finite-difference operators (BDF2 and HWCNS) used in metric term evaluation for free-stream preservation

- 2D nonlinear system is solved at each space marching station using an alternating line Jacobi relaxation

See paper for details

LAVA Framework



Kiris at al. AIAA-2014-0070 & AST-2016

Computational Results

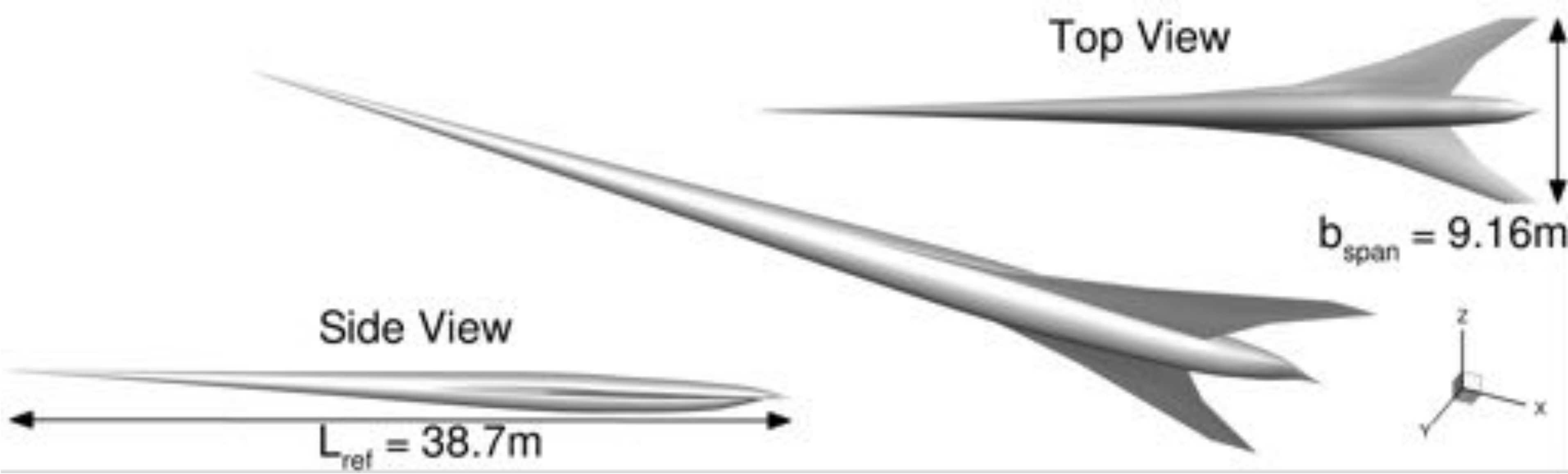
- **JAXA Wing Body**
  - Sensitivity Studies: (see paper for all sensitivity studies)
    - *Mach cone perturbation angle*
    - *Stretching ratio*
    - *Maximum aspect ratio*
    - *Streamwise resolution*
    - *Circumferential resolution*
    - *Circumferential extent*
    - *Metric term evaluation*
    - *Convective flux discretization*
    - *Nonlinear convergence tolerance*
  - Azimuthal Dependence of Nonlinear Wave Propagation
    - Near-Field to Mid-Field
    - Mid-Field to Ground

- **Low Boom Aircraft Wind Tunnel Model**
  - Space Marching Grid and Solution
  - Wind Tunnel Comparison

JAXA Wing Body

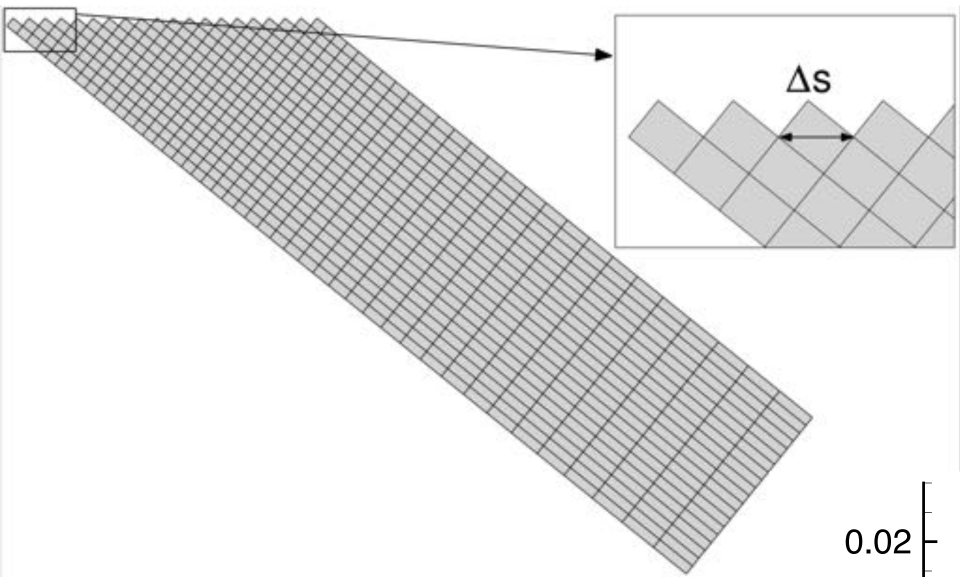
JAXA Wing Body (JWB) configuration from 2nd AIAA Sonic Boom Workshop (SBPW2)

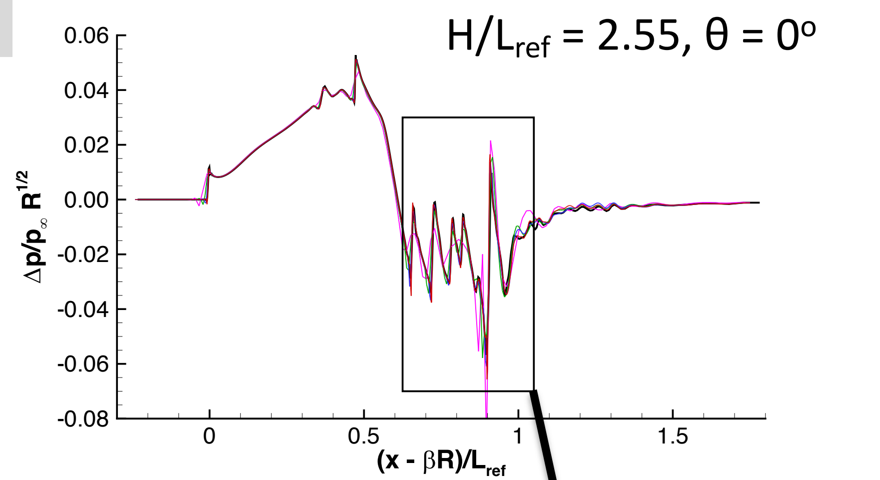
- Designed to achieve low boom levels
- Reference length: L_{ref} = 38.7 m
- Mach = 1.6, Re/m = 5.7 million, and α = 2.3°
- Near-field CFD results using LAVA reported at SBPW2

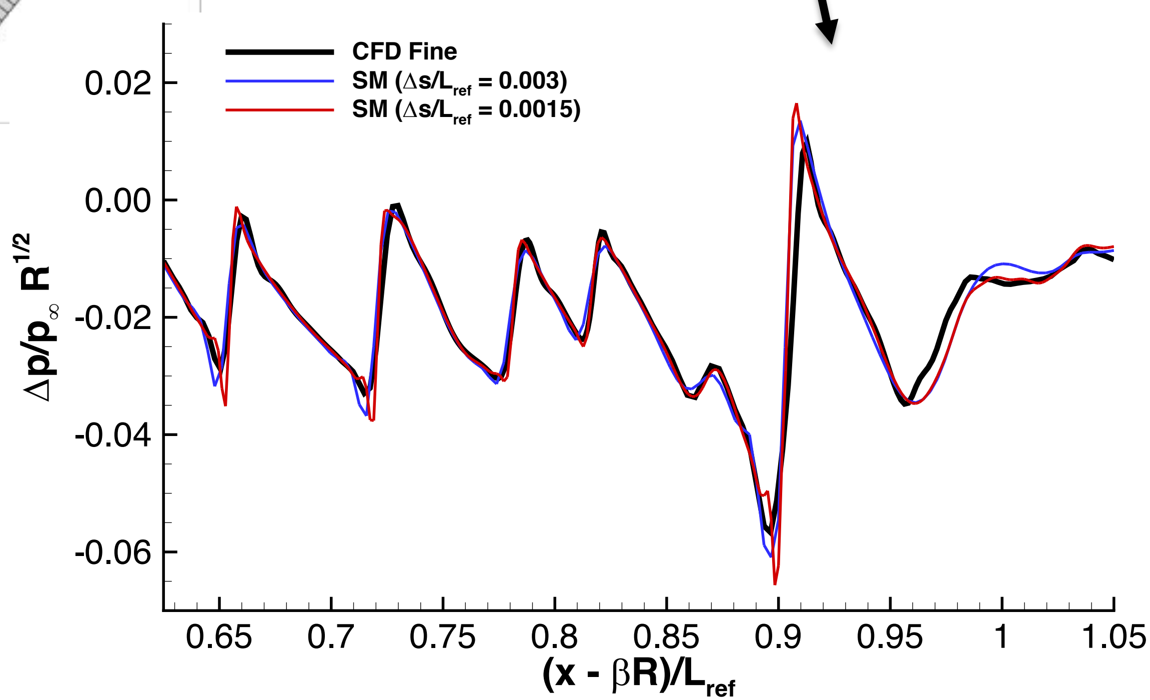


Sensitivity Study (Streamwise Spacing)

Streamwise Spacing $\Delta s/L_{ref}$ = 0.012, 0.006, 0.003, 0.0015

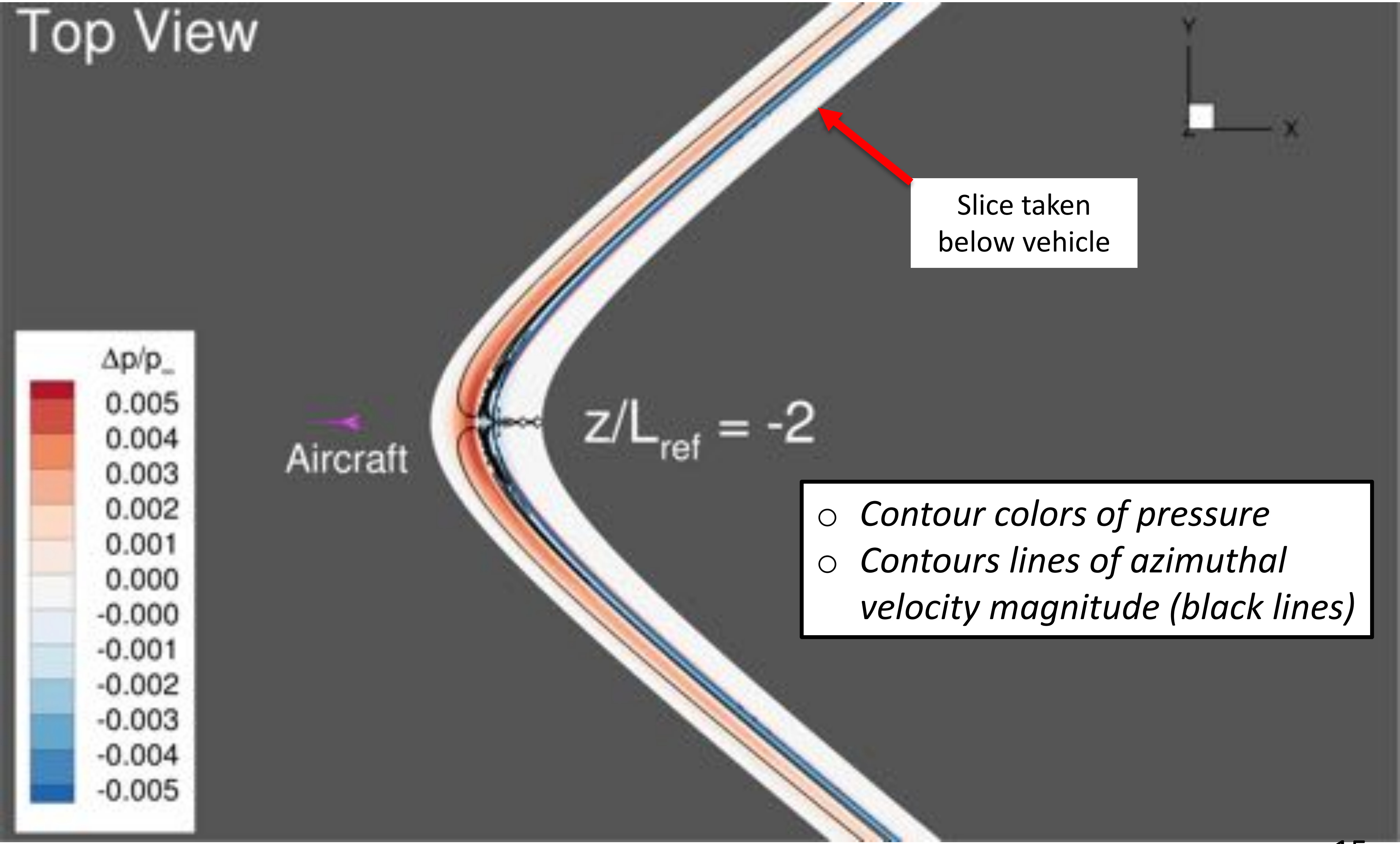






- Generated 4 space marching grid resolutions
- Δs/Lref = 0.003 appears adequate for JWB
- Space marching solution converges to CFD

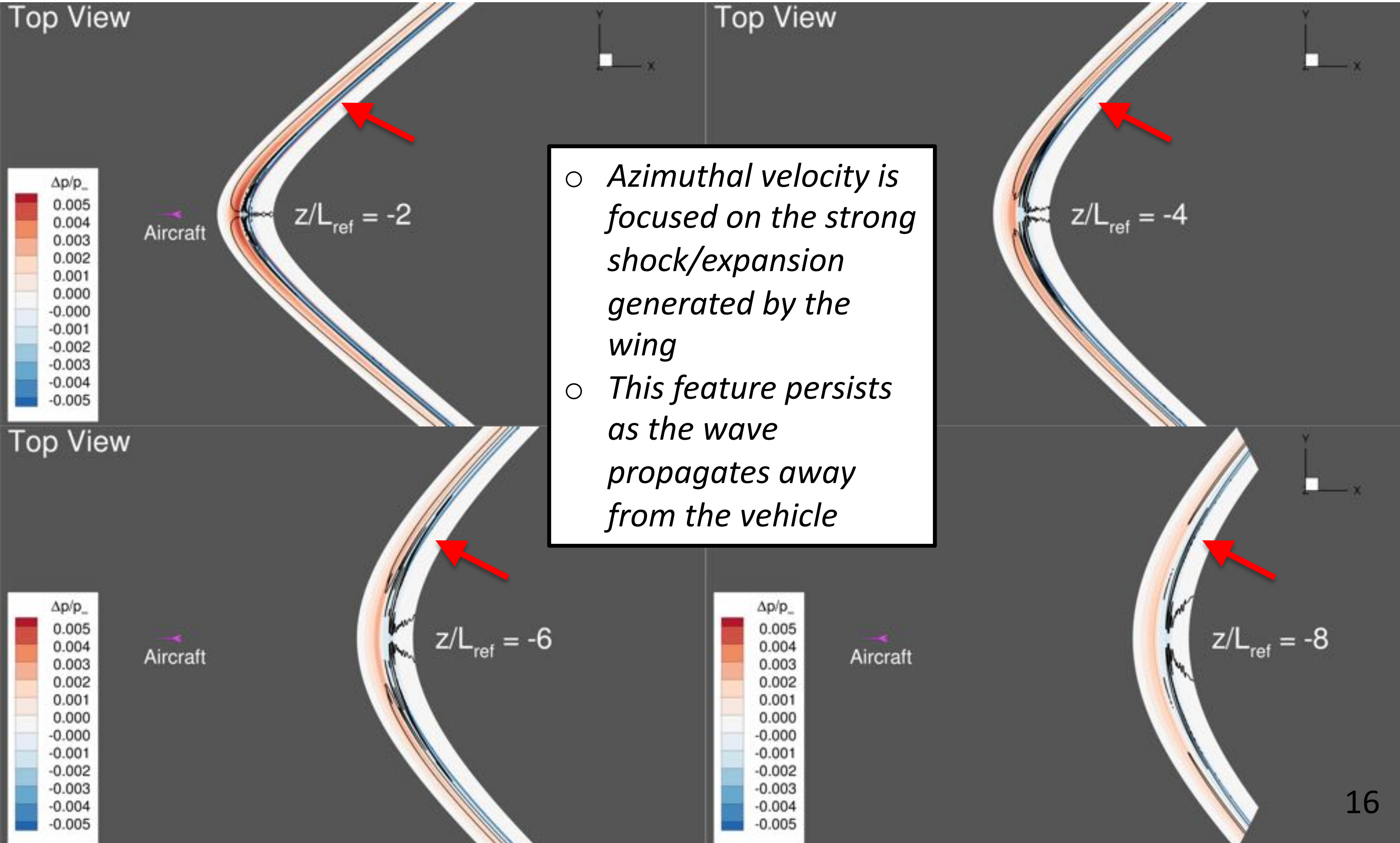
Azimuthal Dependence of Nonlinear Wave Propagation



- Contour colors of pressure
- Contours lines of azimuthal velocity magnitude (black lines)

Azimuthal Dependence of Nonlinear Wave Propagation

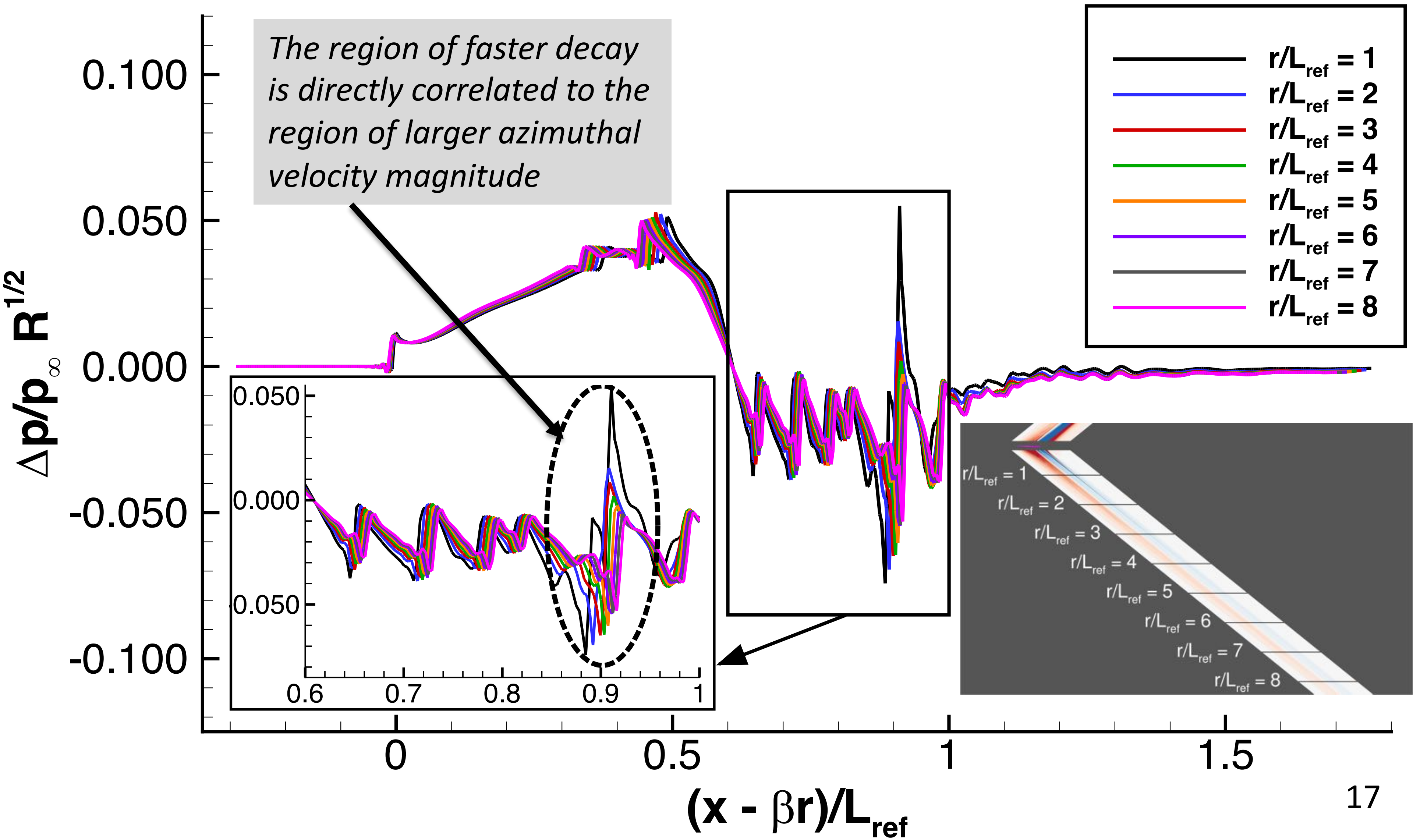
Pressure contour colors with contour lines of azimuthal velocity magnitude



- *Azimuthal velocity is focused on the strong shock/expansion generated by the wing*
- *This feature persists as the wave propagates away from the vehicle*

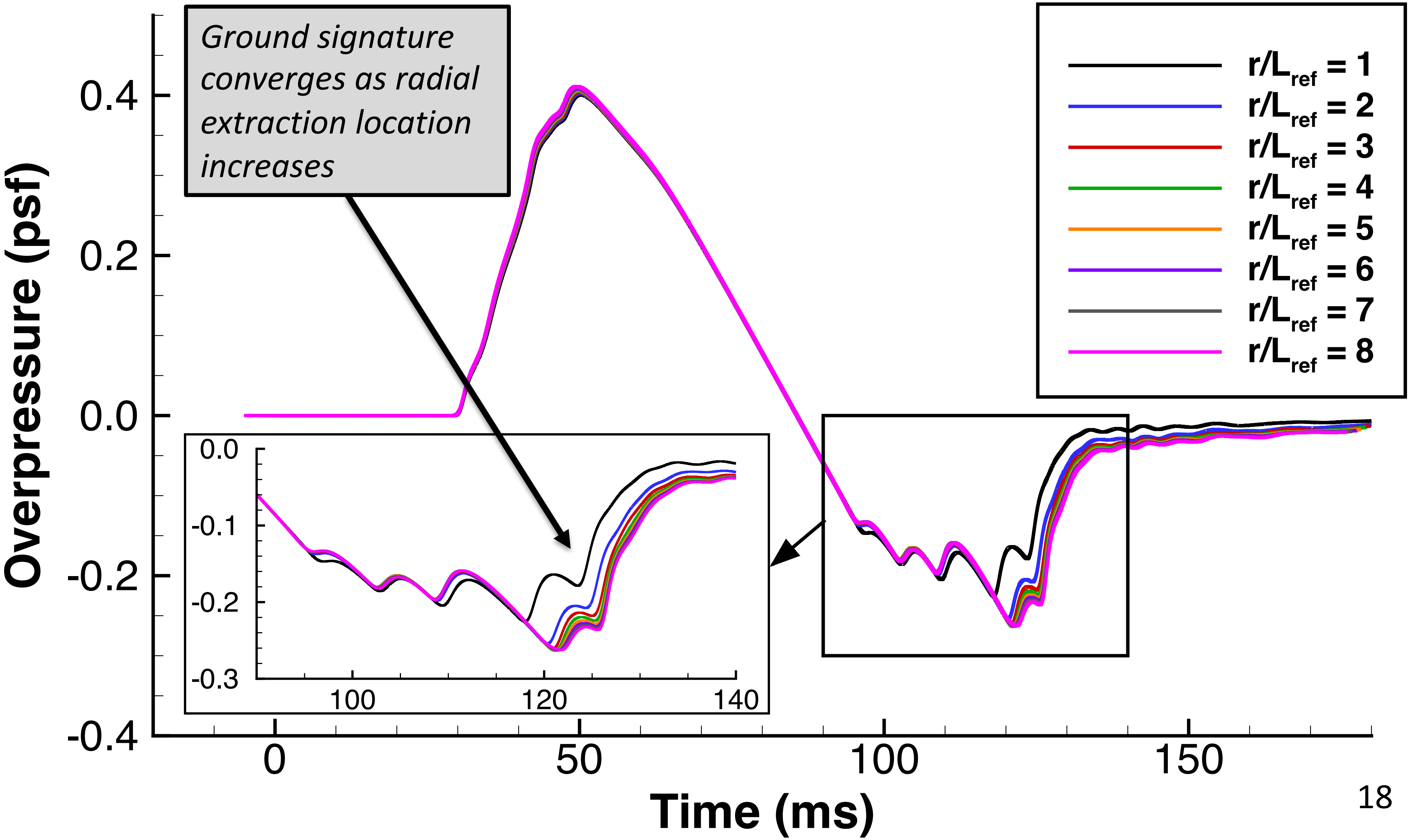
Azimuthal Dependence: Near-Field to Mid-Field

Scaled pressure signatures extracted at 8 different radial locations below the aircraft



Azimuthal Dependence: Mid-Field to Ground

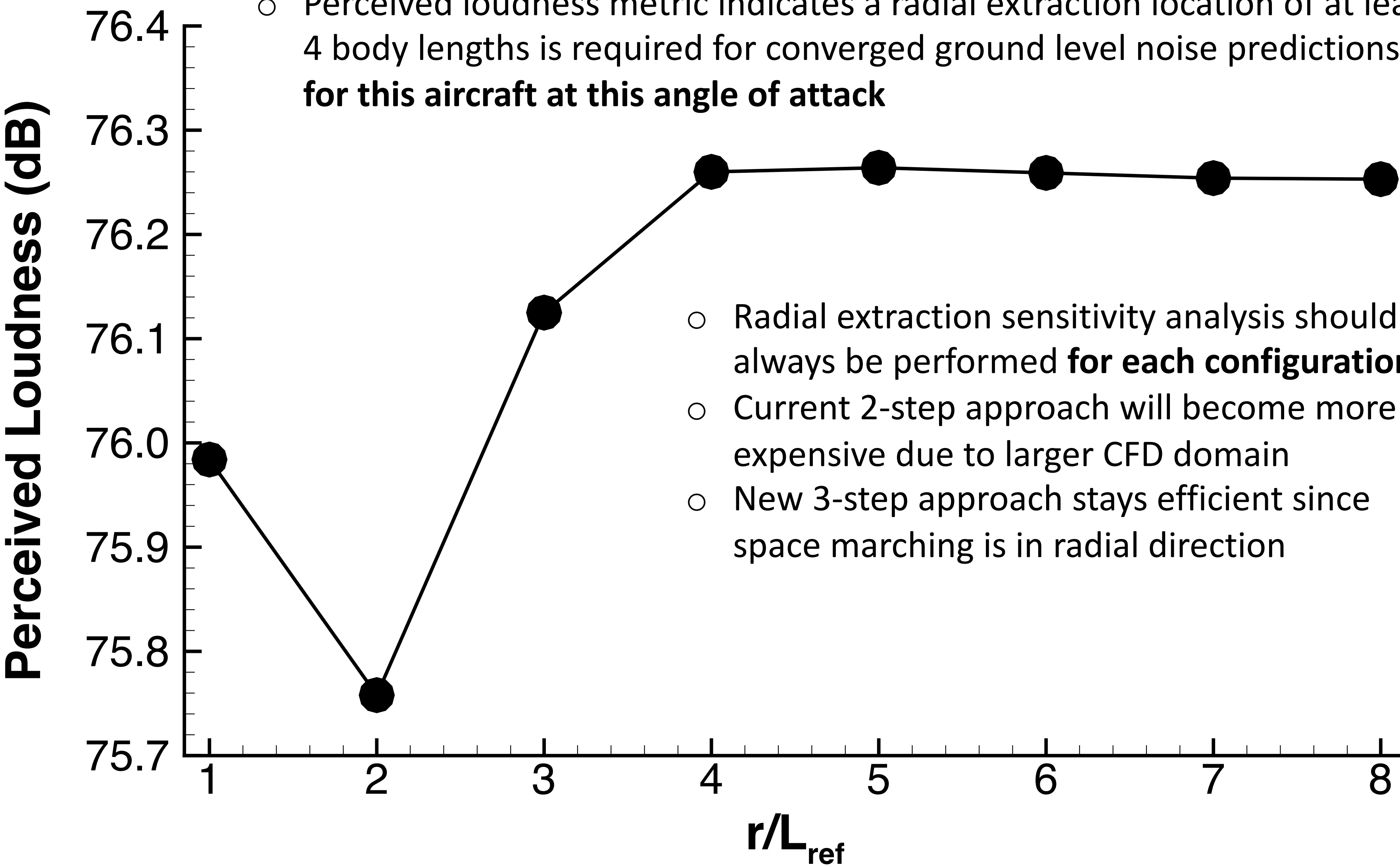
Overpressure ground signatures propagated with sBOOM from each radial extraction



Azimuthal Dependence: Mid-Field to Ground

Perceived loudness on the ground as a function of radial extraction location

- Perceived loudness metric indicates a radial extraction location of at least 4 body lengths is required for converged ground level noise predictions **for this aircraft at this angle of attack**

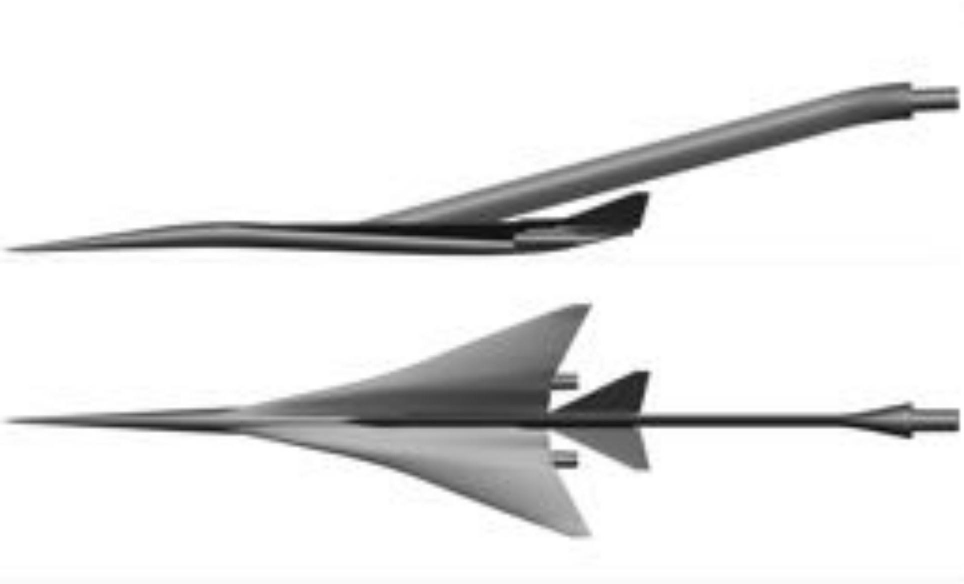


- Radial extraction sensitivity analysis should always be performed **for each configuration**
- Current 2-step approach will become more expensive due to larger CFD domain
- New 3-step approach stays efficient since space marching is in radial direction

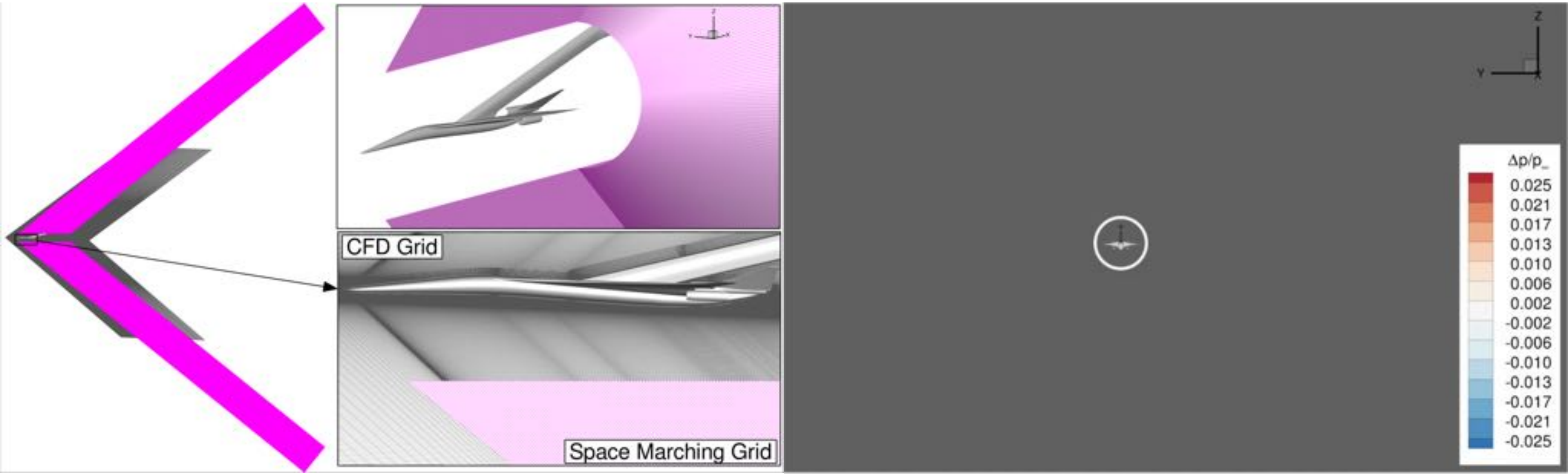
Low Boom Aircraft Wind Tunnel Model

Lockheed Martin Phase I low boom model from 1st AIAA Sonic Boom Workshop (LM1021)

- Designed to achieve low boom on-track signatures
- Reference length: L_{ref} = 22.365 inch (0.568 m) 0.008 percent scale
- Mach = 1.6, Re/m = 4.36 million, and $\alpha = 2.1^{o}$
- Experimental data reported in *Cliff et. al.* (AIAA-2014-0560)
- Near-field CFD results using LAVA reported in *Housman et. al.* (AIAA-2014-2008)

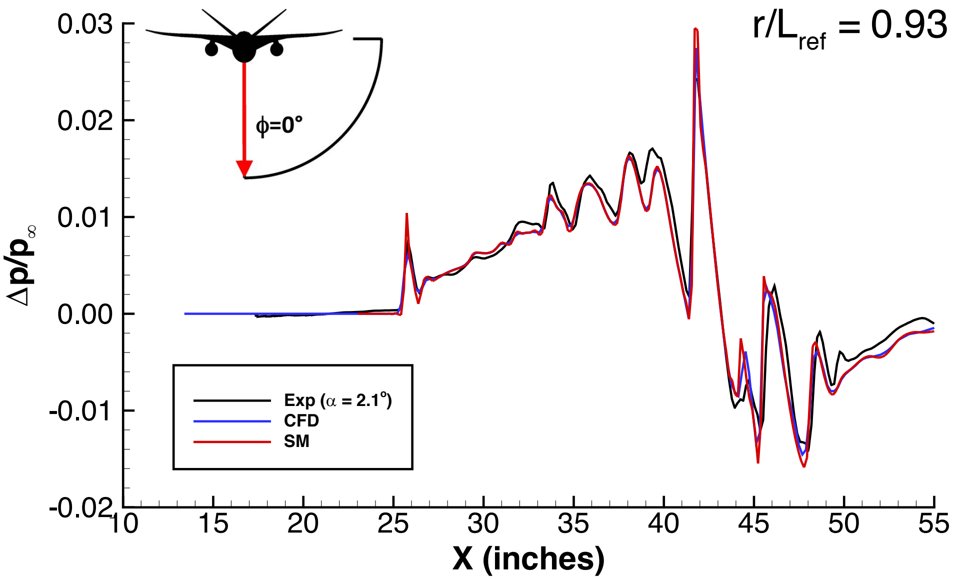


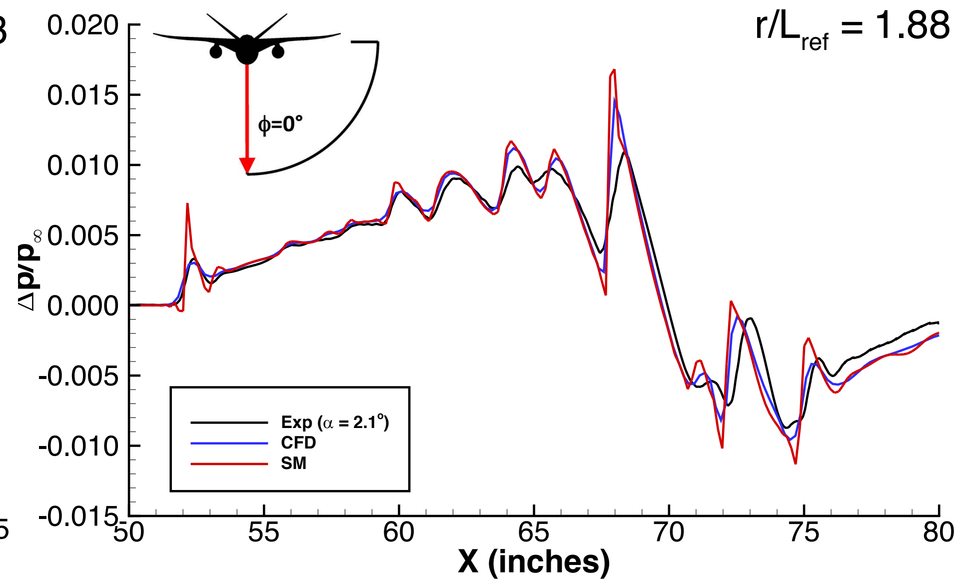
LM1021 Space Marching Grid and Solution

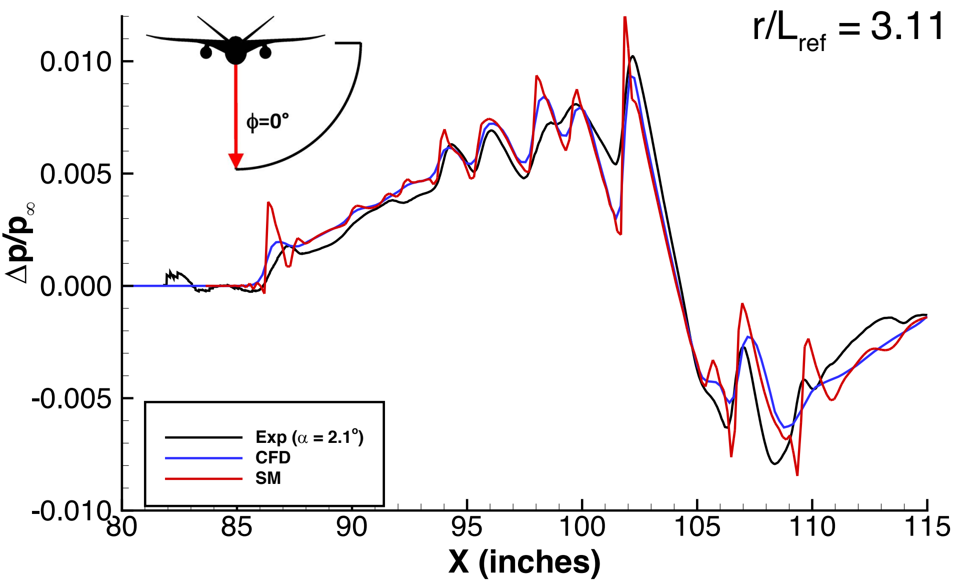


- Inputs for space marching grid generation were taken from grid sensitivity studies (see paper for details)
- SR = 1.05, AR_{max} = 20, $\Delta s/L_{ref}$ = 0.003, $\Delta\theta$ = 1°, θ_{max} = 180°, R = 10 L_{ref}
- Grid Dimensions: 351 x 181 x 564 (35.8 Million points, 4.2 seconds to generate)
- Inputs for space marching solver parameters were taken from solver sensitivity study (HWCNS4-ZWENO5)
- Space marching wall-clock time 106 seconds using 80 threads on single workstation

LM1021 Wind Tunnel Comparison







- Space marching and CFD solutions match wind tunnel data well at r/L_{ref} = 0.93
- As r/L_{ref} increases pressure peaks in wind tunnel data appear smoothed (averaging procedure see Cliff 2014)
- Space marching and CFD solutions retain sharp peaks at larger r/L_{ref}
- Space marching solution shows higher amplitudes than 2nd order CFD

Computational Savings

Example: JAXA Wing Body (66% reduction)

Measured Time (JWB)	2-Step Approach	3-Step Approach
CFD (RANS)	1920 core hrs. (R = $7L_{ref}$)	640 core hrs. (R ~ b/2)
Space Marching*	NA	3 min. 6 seconds (R = $10L_{ref}$)
sBOOM (1 azimuth)	~30 seconds	~30 seconds
Total Time	1920 hrs. 30 sec.	640 hrs. 3 min. 36 sec.

- Total time dominated by near-field CFD with both approaches
- Reduction of CFD domain extend lead to the reduction in total time
- Space marching approach time is small:
  - Space marching grid generation (116.4 Million points 13.6 sec.)
  - Interpolation of CFD solution onto fringe points (7.5 sec. 40 cores)
  - Space marching solution (164.9 sec. 80 threads)

Summary

- ***A high-order accurate space marching method was developed for efficient near-field to mid-field sonic boom propagation***
  - A Mach-cone aligned curvilinear grid using *iblanking* technology was developed which is appropriate for space marching
  - Thorough grid and solver parameter sensitivity studies reported in paper
  - Important azimuthal effects on near-field to mid-field wave propagation and mid-field to ground level noise prediction was demonstrated
  - Completed validation of the near-field to mid-field approach on the LM1021 wind tunnel model

- ***A three-stage process for computing ground level noise from an aircraft was developed***
  - Reduces CFD domain extent by 40 – 60 %
  - Introduces new near-field to mid-field space marching method
    - Space marching grid generated in seconds (automatically)
    - Interpolation from CFD to space marching grid
    - Space marching propagation (up to 10 body lengths) in minutes on a workstation
  - Total time reduction of 66% compared to current approach for the JAXA wing body configuration